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Methodology
Development
Report

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Methodology
Development
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STRUCTURAL DYNAMICS PAYLOAD LOADS ESTIMATES

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FOREWORD

This Methodology Development Report is submitted to the National Aeronautics and Space Administration's George C. Marshall Space Flight Center, Huntsville, Alabama, in response to the contract provisions of deliverable items associated with Structural Dynamics Payload Loads Estimates, Contract Number NAS8-33556.

The author wishes to thank H. Harcrow for supporting this effort.

TABLE OF CONTENTS

NOMENCLATURE

$\{x\}$	the generalized discrete displacement vector
$\{\dot{x}\}$	the generalized discrete velocity vector
$\{\ddot{x}\}$	the generalized discrete acceleration vector
B	booster (as subscript and superscript)
P	payload (as subscript and superscript)
I	interface (as subscript)
N	non-interface (as subscript)
-	with respect to interface (as overbar)
$\{F\}$	applied force vector
$\{R\}$	reaction vector
$[M]$	mass matrix
$[K]$	stiffness matrix
$[I]$	unit matrix
$\{q\}$	modal coordinates
$[\Phi]$	modal matrix
$[T]$	constraint modal matrix (interface included)
$[C]$	damping matrix
$[\omega]$	natural frequency matrix
$[\zeta]$	damping coefficient matrix
$[B], [P]$	coupling matrices
h	time step size
β	parameter
$\{L\}$	internal load vector
$[k]$	stiffness kernel
$[\Psi]$	geometric compatibility matrix
IF	interface dimension
NB	non-interface dimension of booster
NP	non-interface dimension of payload

INTRODUCTION

The United States currently utilizes a rather small family of launch vehicles (boosters) to support a varied spectrum of satellite and spacecraft programs 1 . These launch vehicles have been carefully designed to accommodate a wide range of payload configurations. In general, the payload interfaces with the launch vehicle at a limited subset of candidate structural "hard" points at the payload launch vehicle separation plane. The latest example in the series is the Space Shuttle.

It is important that any candidate payload be designed to withstand the load environment transmitted to the payload from within the shielded payload compartment. Such environments commonly originate from a static (steady state) vehicle acceleration, a transient or dynamic event such as rocket motor ignition, or an acoustical environment. Very often, it is the transient dynamic response behavior of the payload that constitutes payload design load profiles; hence, it is important that proper attention be given to the payload transient response characteristics as influencing major design decisions.

Present analytical techniques by which such design loads are predicted are very costly and time consuming. The calendar turnaround time of a given cycle usually is lengthened when the payload design organization, the booster organization and the payload integration organization are different companies. Indeed, a fair amount of coordination is necessary to make the transfer of information between those three organizations optimal. Unfortunately, this coordination is very difficult to establish, resulting in considerable time delays. Moreover, these costs and delays repeat themselves for every load cycle (i.e., every time a change is made in the booster or payload). A typical example is the development of the Viking Orbiter System [2].

The ever increasing number of modal coordinates necessary to model today's aerospace structures not only increases the cost of a load cycle, but also imposes greater demands on the analyst to keep the models within range of current computer capabilities.

The objective of the present work is to develop a "full-scale" payload integration method which reduces the cost of a load cycle dramatically and will be capable of handling very large systems. This new approach is a "full-scale" method in the sense that it actually solves the coupled booster/payload system equations and does not involve any additional approximations or assumptions as compared to the standard transient analysis.

The present report is part of a research effort into possible developments of so-called "short-cut" methods. A "short-cut" method essentially introduces certain assumptions and/or approximations which partially or completely circumvent the coupling between the booster and the payload. As will be shown in Chapter II, it is indeed possible to derive such "short-cut" methods. However, a "short-cut" method inherently produces approximate system responses and, therefore, approximate design loads. The question then is if the increased cost-effectiveness of such a short-cut method justifies the loss of accuracy in the response and the design loads.

The present "full-scale" method is very cost effective and directly applicable for the shuttle payload design case. This development effective analysis tool without the use of approximation methods. For a comparison of "short-cut" and "full-scale" methods, the reader is referred to References [3] and [4] .

CHAPTER I: A DIRECT INTEGRATION METHOD FOR LOW FREQUENCY ENVIRONMENTS - METHODOLOGY

1. INTRODUCTION

The shear size and complexity of today's aerospace structures has created the need for better and more cost-effective payload integration techniques. Indeed, the cost associated with a typical design load cycle, has become quite substantial. In order to arrive at the optimum design, several of these design load cycles are necessary for a particular event. In addition, for each event various load conditions must be investigated which also add to the total cost of the payload design effort. This section derives methodology of a payload integration method which significantly reduces analysis and design turn around time while retaining the accuracy of a "full-scale" method.

The configuration of multiple payloads connected to the booster through separate interfaces is typical for most Shuttle missions. The fact that many of these payloads are not directly coupled allows for a significant simplification of the booster/payloads system equations. Superfluous interface degrees of freedom on the booster side can be accomodated within the formulation. Superfluous interface degrees of freedom are those interface degrees of freedom which are included in the launch vehicle model but are not connected to any payload. The superfluous interface degrees of freedom arise because the booster organization cannot afford to reconstruct a booster model every time the interface with payload(s) changes.

A numerical integration scheme used to obtain the booster/payload(s) system response is defined. The standard approach is to obtain the so-called "modal modes" i.e. the coupled system modes in order to decouple the system equations. The present approach avoids the solution of such a system eigenvalue problem. A Newmark-Chan-Beta numerical integration scheme is used to directly determine the system response. This technique takes advantage of the peculiar structure of the equations of motion for the system. All zero entries of the system mass and stiffness matrices can be eliminated. In fact, a comparison feature can be implemented so that elements close to zero can be omitted, reducing the cost of the integration routine even more. The comparison feature makes the full-scale method a so-called short-cut method. A full-scale method can be defined as a method which yield "exact" results compared to the standard transient analysis technique, whereas a short-cut method introduces an approximation or assumption which leads to a more cost-effective but less accurate solution.

A Fortran computer program has been written and implemented on the CDC Cyber 172. The final remarks section discuss advantages and disadvantages of the proposed approach.

2. FORMULATION OF THE PROBLEM

The objective of this section is to describe the payload integration problem as it occurs in many of today's engineering applications.

As an example, let us consider the landing of the Shuttle Orbiter (= the delta-wing-airplane-like module) carrying a certain payload (e.g. the space telescope). Obviously, when the orbiter touches the landing strip it will experience reaction forces. These forces will be transmitted to the payload through the interface (i.e. through the connection points between the orbiter and its payload). The payload then, will undergo elastic displacements. The question then is, will the payload be able to withstand those displacements without being damaged? The answer to this question requires a dynamic analysis of the booster/payload system.

First, an analytical booster and payload model is developed. This involves the construction of mass and stiffness matrices, using any suitable method (e.g. the finite element method). These models are usually extremely large (i.e. a very large number of degrees of freedom) and must be reduced to a suitable working size. The reduction of the booster and payload models requires a considerable amount of engineering judgement. Indeed, the objective is to retain enough information or fidelity in the original model and to still arrive at an acceptable working size.

At this point it is possible to derive a coupled booster/payload system model. The key to obtain the system equations is the fact that the displacements at the booster side of the interface must be the same as the displacements at the payload side of the interface. Similarly, the reactions at the interface must be equal in magnitude but opposite in sign. Although the booster/payload system equations could now be solved, in most applications this system would still be large and costly to solve. Fortunately, in many cases the force environment has a rather low frequency content. In our example of the orbiter landing, this would mean that the reaction forces on the orbiter from the landing gear would have a low frequency content (e.g.

< 50 Hz). It is a known fact that if the forcing function has a frequency content below say 50 Hz, that the system response above 50 Hz will be negligible compared to the response below 50 Hz. This at least opens the possibility of truncating the modes and frequencies in the booster and payload model in order to further reduce the size of the system. Although certain precautions must be taken, this approach is indeed a valid one and leads to very accurate results. Consequently, the standard procedure is to solve an eigenvalue problem for both the booster and the payload and write the system equations in terms of these modes and frequencies. The size of the system can then be reduced by truncating all the modes above the so-called cut-off frequency (= 50 Hz in our example). As mentioned above, certain precautions must be taken in order not to lose essential information, especially at the interface.

The next step is to solve the set of system differential equations. This step is usually a very expensive one. The standard approach is to solve the system eigenvalue problem in order to decouple the system. The solution of the uncoupled system equations is then a relatively cost-effective process. Although the system modes can again be truncated according to the cut-off frequency, it is still a very expensive item to obtain these system modes.

Once the system response is calculated, one is now in a position to calculate payload member loads. Indeed, Hooke's law defines the relationship between the displacements in the member and the loads in the member. Note that in practive, one often uses the so-called "acceleration" method to obtain loads, as we shall see later in this report.

Finally, the member loads can be used to obtain maximum stresses and strains and enable the payload designer to determine whether or not the members will be damaged during the landing of the orbiter. Of course, several other events must be evaluated (e.g. ignition, separation, meco, etc.). Moreover, the response/load problem is an iterative one, i.e. that once the designer changes the payload based on a set of design loads we have a new booster/payload system and, therefore, a new set of laods. In general, several so-called load cycles are necessary to arrive at the optimum design. The flow chart on page 24 graphically despicts the essential elements in a load cycle.

From the above, we can conclude that the dynamic analysis part in a design effort is often a very costly item. Consequently, much research has been done in order to improve and make the load cycle more cost-effective [4]. The present report is such an effort. The objective is to make the response-link and the loads-link more cost-effective without sacrificing any accuracy.

3. DERIVATION OF THE BASIC EQUATIONS

The purpose of this section is to derive the basic equations needed for a booster/payload integration effort.

Figure 1 shows the free body diagrams of the booster B and the payload P. The booster and the payload are connected to each other through the interface. Physically, the interface is the collection of structural "hard points" which the booster and the payload have in common. Mathematically, this means that

$$\left\{x_I^B\right\} = \left\{x_I^P\right\} \quad , \quad \left\{R_I^B\right\} = -\left\{R_I^P\right\} \text{ , for } \underline{\text{all}} \text{ times } t \tag{1}$$

From the free body diagrams in Figure 1, we can easily write the equations of motion for the booster B and the payload P as,

$$\left[\begin{array}{c|c} M_B & \\ \hline & M_P \end{array}\right] \left\{\begin{array}{c} \ddot{x}_B \\ \hline \ddot{x}_P \end{array}\right\} + \left[\begin{array}{c|c} K_B & \\ \hline & K_P \end{array}\right] \left\{\begin{array}{c} x_B \\ \hline x_P \end{array}\right\} = \left\{\begin{array}{c} F_B \\ \hline F_P \end{array}\right\} + \left\{\begin{array}{c} 0 \\ R_I^B \\ \hline 0 \\ R_I^P \end{array}\right\} \tag{2}$$

Note that the equations of motion for B and P are still uncoupled and still contain the unknown reactions $\left\{R_I^B\right\}$ and $\left\{R_I^P\right\}$. Several well-known procedures [4] exist to derive the coupled set of system equations, i.e. to eliminate the unknown reactions and redundant interface displacements $\left\{x_I^P\right\}$. One such technique uses interface restrained booster and payload displacements and as will be pointed out later, is ideally suited for our purposes [5].

The basic idea is to construct the following transformations.

$$\left\{x_N^B\right\} = [S_B] \left\{x_I^B\right\} + \left\{\bar{x}_N^B\right\} \tag{3}$$

$$\left\{ x_N^P \right\} = [S_P] \quad \left\{ x_I^P \right\} + \left\{ \bar{x}_N^P \right\} \tag{4}$$

where

$$[S_B] = - [K_{NN}^B]^{-1} \quad [K_{NI}^B] \tag{5}$$

$$[S_P] = - [K_{NN}^P]^{-1} \quad [K_{NI}^P] \tag{6}$$

Using these transformations together with Equation (1), it is possible to write

$$\left\{ \begin{array}{c} x_B \\ \hline x_P \end{array} \right\} = \left\{ \begin{array}{c} x_N^B \\ x_I^B \\ \hline x_N^P \\ x_I^P \end{array} \right\} = \left[\begin{array}{c|c|c} I & S_B & 0 \\ 0 & I & 0 \\ \hline 0 & S_P & I \\ 0 & I & 0 \end{array} \right] \left\{ \begin{array}{c} \bar{x}_N^B \\ \hline x_I^B \\ \hline \bar{x}_N^P \end{array} \right\} \tag{7}$$

This final transformation (7) substituted into Equation (2) will eliminate the redundant set of displacements $\left\{ x_I^P \right\}$ and in the process it will also eliminate the unknown reactions $\left\{ R_I^B \right\}$ abd $\left\{ R_I^P \right\}$, yielding,

$$
\left[\begin{array}{c|c|c}
I_B^T M_B I_B & I_B^T M_B T_B & 0 \\
\hline
T_B^T M_B I_B & T_B^T M_B T_B + T_P^T M_P T_P & T_P^T M_P I_P \\
\hline
0 & I_P^T M_P T_P & I_P^T M_P I_P
\end{array}\right]
\left\{\begin{array}{c}
\ddot{\bar{x}}_N^B \\ \hline \ddot{x}_I^B \\ \hline \ddot{\bar{x}}_N^P
\end{array}\right\}
$$

$$
+ \left[\begin{array}{c|c|c}
I_B^T K_B I_B & 0 & 0 \\
\hline
0 & T_B^T K_B T_B + T_P^T K_P T_P & 0 \\
\hline
0 & 0 & I_P^T K_P I_P
\end{array}\right]
\left\{\begin{array}{c}
\bar{x}_N^B \\ \hline x_I^B \\ \hline \bar{x}_N^P
\end{array}\right\}
$$

$$
= \left\{\begin{array}{c}
I_B^T F_B \\ \hline T_B^T F_B \\ \hline 0
\end{array}\right\} \tag{8}
$$

where we assumed that no forces are acting on the payload P (an assumption which need not be made). Equation (8) represents the coupled booster/payload system of equations of motion in discrete coordinates, using non-interface coordinates for both the payload and the booster. Note that damping can always be included. Furthermore, the matrices $[T_B^T K_B T_B]$ and $[T_P^T K_P T_P]$ are zero only when the interface is determinate.

Next, we introduce the interface-restrained modes $[\phi_N^B]$ and $[\phi_N^P]$ and also the interface modes $[\phi_I^B]$, i.e.

$$
\left\{ \bar{x}_N^B \right\} = [\bar{\phi}_N^B] \left\{ \bar{q}_N^B \right\} , \quad \left\{ \bar{x}_N^P \right\} = [\bar{\phi}_N^P] \left\{ \bar{q}_N^P \right\}
$$
$$
\left\{ x_I^B \right\} = [\phi_I^B] \left\{ q_I \right\} \tag{9}
$$

Using Equation (9) in Equation (8) leads to

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F\} \tag{10}$$

$$[M] = \begin{bmatrix} I & B^T & 0 \\ B & I & P \\ 0 & P^T & I \end{bmatrix}, \quad [C] = \begin{bmatrix} 2\zeta_B\bar{\omega}_B & 0 & 0 \\ 0 & 2\zeta_I\omega_I & 0 \\ 0 & 0 & 2\zeta_P\bar{\omega}_P \end{bmatrix}$$

$$[K] = \begin{bmatrix} \bar{\omega}_B^2 & 0 & 0 \\ 0 & \omega_I^2 & 0 \\ 0 & 0 & \bar{\omega}_P^2 \end{bmatrix} \tag{11}$$

and

$$\begin{aligned} [B] &= [\phi_I^B]^T \, [T_B^T M_B I_B][\bar{\phi}_N^B]\,, \\ [P] &= [\phi_I^B]^T \, [T_P^T M_P I_P][\bar{\phi}_N^P] \end{aligned} \tag{12}$$

$$q = \begin{Bmatrix} \bar{q}_N^B \\ q_I^B \\ \bar{q}_N^P \end{Bmatrix} \qquad F = \begin{Bmatrix} \bar{\phi}_N^{B\,T} I_B^T F_B \\ \phi_I^{B\,T} T_B^T F_B \\ 0 \end{Bmatrix} \tag{13}$$

Note that we also introduced damping. We shall make some more remarks about damping in Chapter II.

At this point one usually truncates the booster and payload modes according to a predetermined "cut-off frequency." This cut-off frequency is based on the significant frequency content of the forcing function $\{F_B\}$. Assuming there are n frequencies below the cut-off frequency, one usually retains $\sqrt{2}$ x n modes. This is a rule of thumb developed from observation of practical modal coupling cases. This rule of thumb allows for a safe margin. Indeed, often times modes with frequencies higher than the cut-off frequency coupie into modes with frequencies smaller than the cut-off frequency and bring about significant perturbations.

Finally, as will be explained in Section 5 of this chapter, it is imperative not to truncate interface modes, even though they might contain modes with frequencies higher than the cut-off frequency.

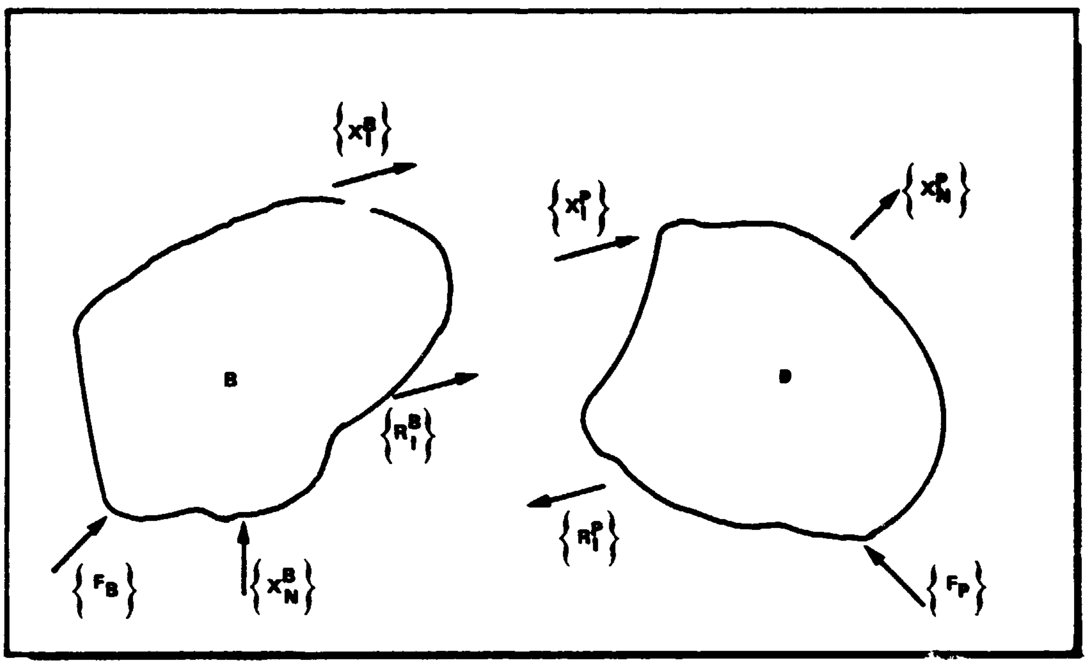

Figure 1 Free-Body Diagrams of Booster B and Payload P

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4. THE NUMERICAL INTEGRATION SCHEME

The objective of this section is to choose a suitable integration scheme to directly integrate Equation (10). This is in contrast with the usual approach, where a new eigenvalue problem with [M] and [K] as mass and stiffness matrix is solved.

It is important to recognize that system (10) can have a frequency content much higher than the cut-off frequency of the forcing term. Usually, those higher frequencies will not produce significant responses. Therefore, a suitable numerical technique should be capable of using a stepsize h, which reflects only the highest frequency of interest but at the same time remains numerically stable. For example, a Runge-Kutta routine would not be suitable because it requires a time-step consistent with the highest frequency in the system, even though these high frequencies may not be of interest to the analyst. Although there are techniques to obtain a good estimate of the highest system frequency, using such a frequency to determine the stepsize would unnecessarily increase the cost of the response routine.

A method that satisfies above constraints is given by the Newmark-Chan-Beta integration method:

$$\{\dot{q}\}_{i+1} = \{\dot{q}\}_i + (1-\sigma)h\{\ddot{q}\}_i + \sigma h\{\ddot{q}\}_{i+1} \tag{14}$$

$$\{q\}_{i+1} = \{q\}_i + h\{\dot{q}\}_i + (\tfrac{1}{2}-\beta)h^2\{\ddot{q}\}_i + \beta h^2\{\ddot{q}\}_{i+1} \tag{15}$$

$$[M]\{\ddot{q}\}_{i+1} + [C]\{\dot{q}\}_{i+1} + [K]\{q\}_{i+1} = \{F\}_{i+1} \tag{16}$$

where the method is unconditionally stable if $\beta > (2\sigma+1)^2/16$. Artificial positive damping is introduced when $\sigma > 0.5$, and artificial negative damping if $\sigma < 0.5$. Good values for our purposes are $\sigma = 0.5$ and $\beta = 0.25$. Theoretically, the time step h can then be given any value while the scheme remains stable. In fact for very large values of h, the scheme generates the static solution of Equation (10). Also

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the scheme will damp out the highest (and least important) modes while preserving the lower ones. In addition, as we shall see shortly, the Newmark-Chan-Beta scheme is capable of taking advantage of the peculiar structure of the present equations of motion. Indeed, let us substitute Equations (14) and (15) into (16) and obtain

$$[M + \sigma hC + \beta h^2_K]\{\ddot{q}\}_{i+1} = \{F\}_{i+1} - [C + hK]\{\dot{q}\}_i - [(1-\sigma)hC + (\tfrac{1}{2}-\beta)h^2K]\{\ddot{q}\}_i - [K]\{q\}_i \tag{17}$$

or, using Equation (11), we can write

$$\begin{bmatrix} D_1 & B^T & 0 \\ B & D_2 & P \\ 0 & P^T & D_3 \end{bmatrix} \begin{Bmatrix} \ddot{\bar{q}}^B_{Ni+1} \\ \ddot{q}^B_{Ii+1} \\ \ddot{\bar{q}}^P_{Ni+1} \end{Bmatrix} = \begin{Bmatrix} f_{Bi} \\ f_{Ii} \\ f_{Pi} \end{Bmatrix} \tag{18}$$

where

$$f_{Bi} = \bar{\Phi}^{B\,T}_N I^T_B F_{Bi+1} - D_4\dot{\bar{q}}^B_{Ni} - D_7\ddot{\bar{q}}^B_{Ni} - \bar{\omega}^2_B q^B_{Ni} \tag{19}$$

$$f_{Ii} = \Phi^{B\,T}_I T^T_B F_{Bi+1} - D_5\dot{q}^B_{Ii} - D_8\ddot{q}^B_{Ii} - \omega^2_I q^B_{Ii} \tag{20}$$

$$f_{Pi} = - D_6\dot{\bar{q}}^P_{Ni} - D_9\ddot{\bar{q}}^P_{Ni} - \bar{\omega}^2_P \bar{q}^P_{Ni} \tag{21}$$

and

$$
\begin{aligned}
D_1 &= I + 2\sigma h\zeta_B\bar{\omega}_B + \beta h^2\bar{\omega}_B^2 \\
D_2 &= I + 2\sigma h\zeta_I\omega_I + \beta h^2\bar{\omega}_I^2 \\
D_3 &= I + 2\sigma h\zeta_P\bar{\omega}_P + \beta h^2\bar{\omega}_P^2 \\
D_4 &= 2\zeta_B\bar{\omega}_B + h\bar{\omega}_B^2 \\
D_5 &= 2\zeta_I\omega_I + h\omega_B^2 \\
D_6 &= 2\zeta_P\bar{\omega}_P + h\bar{\omega}_P \\
D_7 &= 2(1-\sigma)h\zeta_B\bar{\omega}_B + (\tfrac{1}{2}-\beta)h^2\bar{\omega}B^2 \\
D_8 &= 2(1-\sigma)h\zeta_I\omega_I + (\tfrac{1}{2}-\beta)h^2\omega_I^2 \\
D_9 &= 2(1-\sigma)h\zeta_P\bar{\omega}_P + (\tfrac{1}{2}-\beta)h^2\bar{\omega}_P^2
\end{aligned}
\tag{22}
$$

are diagonal matrices. Consequently, the evaluation of f_{Bi}, f_{Ii}, and f_{Pi}, are very cost-effective. Also, note that D_i $(i=1,\ldots,9)$ are one-time calculations.

Normally, the solution for $\{\ddot{q}\}_{i+1}$ in Equation (13) requires a triangular decomposition and must be repeated for every h. However, in this case the unique form of the coefficient matrix of $\{\ddot{q}\}_{i+1}$ makes it possible to avoid such decompositions. Moreover, it is possible to completely take advantage of the diagonal and zero partitions appearing in that coefficient matrix.

First, let us premultiply Equation (18) by $[-BD_1^{-1} \quad I \quad -BD_3^{-1}]$ which yields the following expression for $\{\ddot{q}^B_{I\,i+1}\}$,

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$$\left\{q^B_{Ii+1}\right\} = \left\{A_1 \quad A_2 f_{Bi} \quad + \quad f_{Ii} \quad + \quad A_3 f_{Bi}\right\} \tag{23}$$

with

$$A_1 \quad = \quad [D_2 \quad +A_2 B^T \quad + \quad A_3 P^T]^{-1} \tag{24}$$

$$A_2 \quad = \quad -BD_1^{-1} \quad , \quad A_3 \quad = \quad -PD_3^{-1} \tag{25}$$

Furthermore, from Equation (18), we easily obtain

$$\left\{\dot{q}^B_{Ni+1}\right\} \quad = \quad \left\{D_1^{-1} f_{Bi} \quad + \quad A_2^T q^B_{Ii+1}\right\} \tag{26}$$

$$\left\{\dot{q}^P_{Ni+1}\right\} \quad = \quad \left\{D_3^{-1} f_{Pi} \quad + \quad A_3^T q^B_{Ii+1}\right\} \tag{27}$$

Equations (23) , (26) , and (27) represent the final set of recurrence relations replacing Equation (18). Note that Equation (24) represents the inversion of an IFxIF matrix where IF is relatively small in many applications. This effectively removes the problem of triangular decomposition of a large matrix. Also, note that the cost of the algorithm primarily comes from multiplications involving matrices A_1, A_2, and A_3, Note however, that their dimensions are IFxIF , IFxNB and IFxNP respectively. Again, in many cases IF is a rather small number. In addition, the routine requires much less core memory which allows for the solution of much larger problems.

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5. THE LOAD TRANSFORMATION

The purpose of this section is to briefly review the "acceleration" approach to calculating loads and at the same time point out some possible savings. An elementary member load transformation can be written as

$$\{L\} = [k\Psi]\{x_P\} \tag{28}$$

Therefore, once the system response is known one can substitute the displacement vector $\{x_P\}$ into Equation (28) and obtain the member loads. This direct approach is called the "displacement" method. In many cases, this is a perfectly valid approach especially if all the modes in Equations (9) and (12) are kept. However, if modes are truncated according to a cut-off frequency this procedure often leads to inaccurate results. This can be corrected by using the so-called "acceleration" method whereby x_P is replaced in terms of applied forces and accelerations using the system equations of motion without damping.

Hruda and Jones [8] introduced a load transformation consistent with modal synthesis techniques. In terms of the present notation Equation (28) can be replaced by

$$\{L\} = [LT1]\begin{Bmatrix} \ddot{\bar{q}}_N^P \\ \ddot{q}_I^B \end{Bmatrix} + [LT2]\{x_I^B\} \tag{29}$$

where

$$[LT1] = [k\Psi][I_P E_P I_P^T][-M_P](I_P\bar{\Phi}_N^P \mid T_P) \tag{30}$$

$$[LT2] = [k\Psi][T_P] \tag{31}$$

and $[E_P] = [I_P^T K_P I_P]^{-1}$. Note that $[LT2] = 0$ when the interface is determinate.

Normally, the displacement vector $\{x_I^B\}$ in Equation (29) must be written in terms of forces and accelerations using the second partition in Equation (8). This not only increases the cost of the procedure, but also introduces the booster accelerations $\{\ddot{\bar{q}}_N^B\}$ and forces $\{F_B\}$ into the problem. We shall now show that this is not necessary if <u>all</u>

interface modes are retained in $[\Phi_I^B]$.

From Equation (8), for an indeterminate interface we can write

$$
\begin{aligned}
\left\{x_I^B\right\} = \; & [T_B^T K_B T_B + T_P^T K_P T_P]^{-1} \; ([T_B]^T \left\{F_B\right\} \\
& -[T_B^T M_B I_B]\left\{\ddot{x}_N^B\right\} - [T_P^T M_P I_P]\left\{\ddot{x}_N^P\right\} \\
& -[T_B^T M_B T_B + T_P^T M_P T_P]\left\{\ddot{x}_I^B\right\})
\end{aligned} \tag{32}
$$

At this point one can introduce the modal accelerations using the transformations (9), yielding

$$
\begin{aligned}
\left\{x_I^B\right\} = \; & [T_B^T K_B T_B + T_P^T K_P T_P]^{-1}([T_B]^T \left\{F_B\right\} \\
& -[T_B^T M_B I_B \bar{\Phi}_N^B]\left\{\ddot{q}_N^B\right\} - [T_P^T M_P I_P \bar{\Phi}_N^P]\left\{\ddot{q}_N^P\right\} \\
& -[T_B^T M_B T_B + T_P^T M_P T_P][\Phi_I^B]\left\{\ddot{q}_I^B\right\})
\end{aligned} \tag{33}
$$

This is the expression that ordinarily must be used in Equation (29). However, <u>if and only if</u> we keep <u>all</u> the interface modes in $[\Phi_I^B]$ we can write that $[T_B^T K_B T_B + T_P^T K_P T_P]^{-1} = [\Phi_I^B][\omega_I^2]^{-1}[\Phi_I^B]^T$.

In addition we can then write $\left\{x_I^B\right\} = [\Phi_I^B]\left\{q_I^B\right\}$ without any loss of accuracy. Using these facts in Equation (33) and taking damping into account, we obtain:

$$
\begin{aligned}
\left\{q_I^B\right\} = \; & [\omega_I^2]^{-1}([\Phi_I^B]^T[T_B]^T \left\{F_B\right\} \\
& -[\Phi_I^{B^T} T_B^T M_B I_B \bar{\Phi}_N^B]\left\{\ddot{q}_N^B\right\} - [2\zeta_I\omega_I] \left\{\dot{q}_I^B\right\} \\
& -[\Phi_I^{B^T} T_P^T M_P I_P \bar{\Phi}_N^P]\left\{\ddot{q}_N^P\right\} - \left\{\ddot{q}_I^B\right\})
\end{aligned} \tag{34}
$$

which is exactly what we obtain from the second partition of Equation (10). Therefore, Equations (29-31) can be replaced by:

$$
\left\{L\right\} = [LT1]\left\{\begin{array}{c} \ddot{q}_N^P \\ \hline \ddot{q}_I^B \end{array}\right\} + [LT2]\left\{\dot{q}_I^B\right\} \tag{35}
$$

where this time,

$$[LT1] = [k\Psi][I_P E_P I_P^T][-M_P](I_P \bar{\Phi}_N^P \mid T_P \Phi_I^B) \qquad (36)$$

$$[LT2] = [k\Psi][T_P \Phi_I^B] \qquad (37)$$

Next, let us write Equation (36) as follows:

$$[LT1] = [k\Psi][I_P](-[E_P][I_P^T M_P I_P][\bar{\Phi}_N^P] \mid$$
$$- [E_P][I_P^T M_P T_P][\Phi_I^B]) \qquad (38)$$

It is now relatively easy to show that $[E_P][I_P^T M_P I_P][\bar{\Phi}_N^P] = [\bar{\Phi}_N^P][\bar{\omega}_P^2]^{-1}$ even when not all the payload modes are retained in $[\bar{\Phi}_N^P]$. Therefore, Equation (38) can be written as,

$$[LT1] = [k\Psi][I_P](-[\bar{\Phi}_N^P][\bar{\omega}_P^2]^{-1} \mid$$
$$- [E_P][I_P^T M_P T_P][\Phi_I^B]) \qquad (39)$$

Using Equations (35), (37) and (39) has several advantages over the approach outlined in Reference [8]. First, in case the interface is indeterminate (i.e. if LT2 $\neq$ 0) it is not necessary to use Equation (32) for $\left\{ x_I^B \right\}$, if and only if we keep all the interface modes $[\Phi_I^B]$. This not only makes the evaluation of Equation (35) much simpler, but also reduces the amount of information to be stored in the course of the response calculations (i.e. only $\left\{ \dot{\bar{q}}_N^P \right\}$, $\left\{ \dot{q}_I^B \right\}$ and $\left\{ q_I^B \right\}$ must be stored). Secondly, the rather expensive evaluation of $[\alpha] = -[k\psi][I_P][E_P][I_P^T M_P I_P][\bar{\Phi}_N^P]$ as proposed in Reference 8 is now replaced by the more efficient computation of $[\beta] = [\bar{\Phi}_N^P][\omega_P^2]^{-1}$. Indeed, applying unit loads successively to each of the non-interface dofs., often becomes a rather expensive item, considering the potentially very large payload models. The other term in Equation (38), $[\gamma] = -[k\Psi][I_P][E_P][I_P^T M_P T_P][\Phi_I^B]$ can easily be evaluated by first forming the product $[I_P^T M_P T_P][\Phi_I^B]$, the columns of which can be looked upon as inertial loads applied at the interface of the payload. The corresponding deflections are equal to $[\varepsilon] = [E_P][I_P^T M_P T_P][\Phi_I^B]$. Note that $[E_P]$ need not to be recomputed, i.e. no decomposition of $[I_P^T K_P I_P]$ is necessary since this has already been done in the modes calculations. Finally, one can also evaluate $[\varepsilon] = [T_p \phi_I^B]$ inexpensively in Equation (37) so that we obtain

$$[LT1] = [k\Psi]([\beta],[\delta]) \tag{40}$$

$$[LT2] = [k\Psi][\varepsilon] \tag{41}$$

Observe that the payload organization can easily save $[\beta]$, $[\delta]$ and $[\varepsilon]$ so that any member in the payload can now be investigated without recalculating these matrices. Observe that Reference 8 requires the payload analyst to make the choice of members before the evaluation of Equations (40) and (41). If for some reason an additional member has to be investigated a reevaluation of LT1 and LT2 is necessary.

Finally, it should also be noted that the loads calculation does not involve the "modal modes" which reduces the computational cost even more.

6. CONCLUSIONS AND SUMMARY

A new payload integration approach has been presented. It is a "full-scale" approach in the sense that it does not introduce new assumptions or approximations compared to the conventional "exact" solution techniques. Improvements over the conventional techniques are introduced in both the response and loads calculations.

The response analysis uses an adaptation of the Newmark-Chan-Beta numerical integration technique. This integration scheme is directly applied to the coupled system equations (i.e. booster/payload system) thereby avoiding the expensive solution of a system eigenvalue problem. The Newmark-Chan-Beta technique has the convenient feature that the step size can be based on the "cut-off frequency" associated with the forcing function regardless of the highest system frequency. This particular feature is necessary in the present method because the highest system frequency is not known a priori. Although there are techniques to determine the highest frequency, it is very likely that this highest frequency will be much larger than the cut-off frequency which would lead to a much smaller time step. It should also be noted that the present approach allows for the solution of much larger systems.

Next, we derived a load transformation consistent with the above modal synthesis method. Several cost saving features were introduced. First, we showed that in the case of an indeterminate interface it is not necessary to write the interface displacements in terms of accelerations and forces, provided one keeps all the interface modes. Incidently, one could actually keep the discrete interface displacements instead of introducing the interface modes. Secondly, it was shown that several simplifications can be affected in the calculation of [LT1] and [LT2] leading to a more efficient and convenient loads calculation. Finally, it should also be pointed out that we do not involve system modes which reduces the cost and simplifies the analysis.

It is estimated that the present approach will reduce the computer cost of a payload integration effort by a considerable amount. Considering the numerous load cases that must be considered in the course of a design effort, the present approach may prove to be of great value.

It should also be pointed out that this technique can easily be adapted to a "short-cut" method. Indeed, Section 4 of Chapter II will be devoted to outlining several possible short-cut procedures.

Finally, also note that the method as presented in Section 4 is considerably more cost-effective than the one presented in Reference 10.

CHAPTER II: A DIRECT INTEGRATION METHOD FOR LOW FREQUENCY ENVIRONMENTS - IMPLEMENTATION

1. INTRODUCTION

This chapter discusses in general terms the software package associated with a complete booster/payload response and loads analysis. An attempt will be made to clearly link the theory of Chapter I with the specific program and subroutine descriptions. This will give us the opportunity to touch upon some of the constraints and difficulties invariably associated with the development of a practical payload integration software package. Some factors to consider are: computer core usage; convergence; available data; the separation of booster, payload and integration organizations; work schedules; engineering time; ease of program usage; computer cost and related efficiency of algorithms; reuse of existing information; required accuracy versus cost; handling of potentially large models; etc.

Section 2 of this chapter presents a general description of the organization and components of the software package. In particular, we explain the purpose and contents of the components and how they relate to each other.

Section 3 presents a simple sample problem and how it is analyzed and evaluated. Also, preliminary results of more realistic analyses will be included.

Finally, conclusions and possible short-cut approaches are introduced in Section 4.

2. ORGANIZATION - GENERAL DESCRIPTION

This section outlines the organization of the software package. The figure 2 represents a flow diagram of a complete booster/payload integration problem. Each of the flow diagram blocks has a program associated with it. Therefore, there are six programs: PROGRAM BOOSTER, PROGRAM PAYLOAD, PROGRAM INTFACE, PROGRAM FORCE, PROGRAM SYSRESP, AND PROGRAM LOADS. Each of these programs draws on a pool of subroutines called FORMA (FORTran Matrix Analysis). FORMA is a library of subroutine coded in FORTRAN IV for the efficient solution of structural dynamics problems. These subroutines are in the form of building blocks that can be put together to solve a large variety of structural dynamics problems. The FORMA library was developed by the Dynamics and Loads Section at Martin Marietta Aerospace and is being updated and expanded whenever the need occurs [11] .

It should be pointed out that other libraries can be used and that the proposed integration method does in no way inherently depend on the FORMA library. However, in this report, the software is built around the FORMA subroutine library (in particular, the Partition-Logic version) and therefore, the user is assumed to have a working knowledge of that library.

There are several reasons motivating the PROGRAM apporach. Because all FORMA routines are written in terms of variable dimensions, it is possible to write each PROGRAM for the specific dimensions of the problem at hand, thereby optimizing computer core usage. Also, the user often has at his/her disposal data already generated by other means. The PROGRAM approach allows the user to omit the recalculation of that particular data. For example, a set of so-called expanded modes could be available. The user then can directly read those expanded modes into the PROGRAM and omit the use of a subroutine which calculates those expanded modes. Furthermore, the PROGRAM approach allows for the separation of data generated by the booster, payload and integration organizations. Indeed, very often these three organizations are physically at different locations and data peculiar to one organization often is not readily available to the other organizations. PROGRAM BOOSTER for example, only deals with data pertaining to the booster and

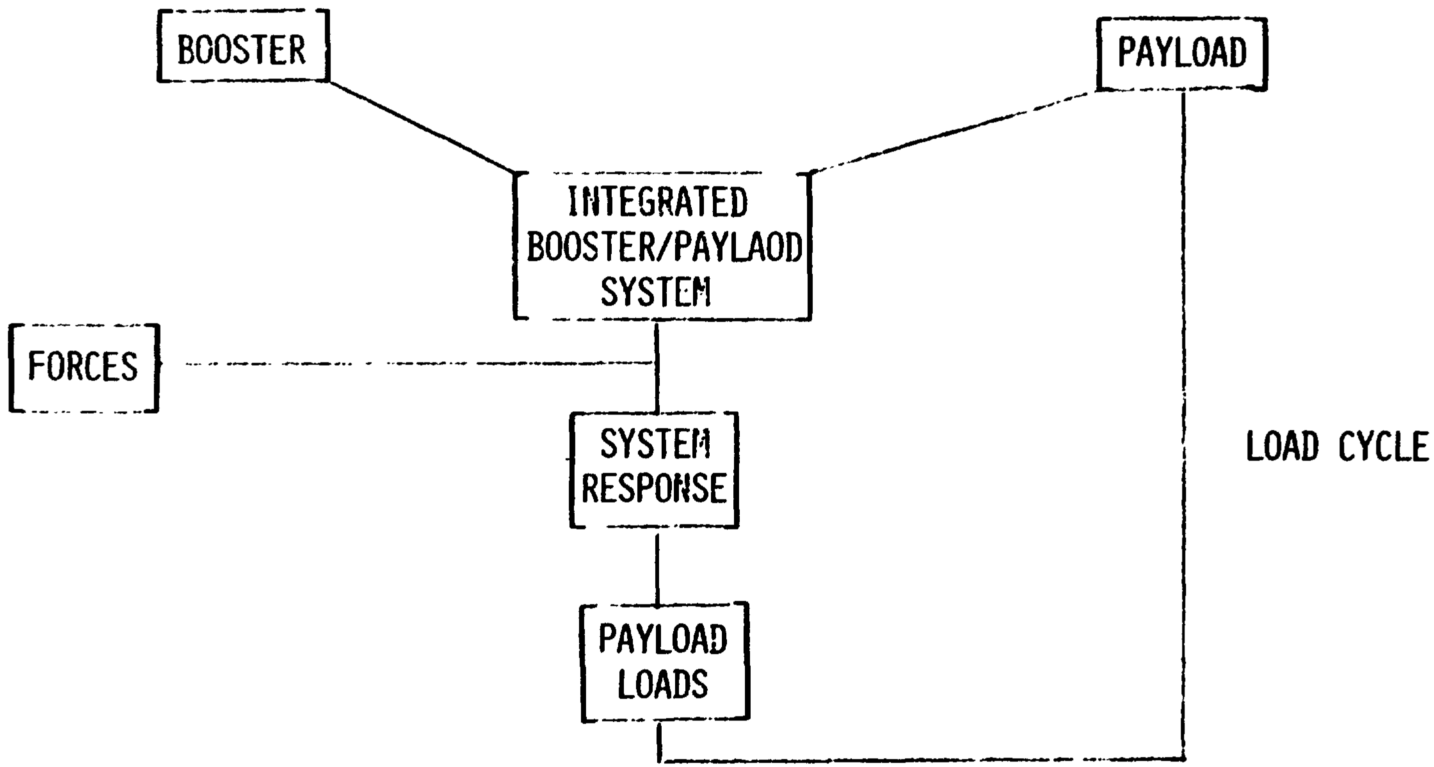

Figure 2: PAYLOAD INTEGRATION PROBLEM

therefore, works independent of the payload. Also, sometimes the data generated by PROGRAM BOOSTER can be used in analyses of different payloads and therefore have not to be recalculated.

Finally, the PROGRAM approach also allows for better check-out and control of the data generated at several points in the process of a load cycle. Indeed, the user can put in his/her own checks if desired.

PROGRAM SYSRESP respresents the hub around which the other five programs are centered. The purpose of PROGRAM SYSRESP is to generate the coupled booster/payload system response. The most important subroutine called by PROGRAM SYSRESP is SUBROUTINE SRESP, which implements the integration scheme as outlined in Section 4 of Chapter I. The INPUT to PROGRAM SYSRESP consists of all the quantities necessary to run SUBROUTINE SRESP. The OUTPUT of PROGRAM SYSRESP is the system response i.e. displacements, velocities and accelerations. These quantities can be written on paper and tape. In particular, the payload accelerations and the booster/payload interface displacements at each time step are written on tape so that they can be used in PROGRAM LOADS for the calculation of member loads.

Much of the INPUT to PROGRAM SYSRESP is not directly given and therefore must be created in advance. PROGRAM BOOSTER, PROGRAM PAYLOAD and PROGRAM FORCE were composed to serve this purpose. PROGRAM BOOSTER generates all booster data necessary to run PROGRAM SYSRESP. The booster organization can use this PROGRAM independently of any other organization. Enough subroutines were developed so that all booster data can be generated starting with the free mass and stiffness matrices $[M_B]$ and $[K_B]$ and the interface restrained modes and frequencies $[\bar{\Phi}_N^B]$ and $[\bar{\omega}_B^2]$. It is reasonable to expect that these INPUT quantities are available. If not, the user is expected to provide this information before running PROGRAM BOOSTER. It would not be wise to "can" the construction of $[M_B]$,$[K_B]$,$[\bar{\Phi}_N^B]$ and $[\bar{\omega}_B^2]$ because of the multitude of ways these quantities can be generated. Furthermore, PROGRAM BOOSTER contains a number of "flags" which allow for user flexibility of INPUT. Indeed, often times certain quantities are already available and need not to be regenerated. The same is true for PROGRAM PAYLOAD which is very similar to PROGRAM BOOSTER except that it generates payload quantities necessary to run PROGRAM SYSRESP. In addition, it also generates parts of load transformations if desired. Again, much flexibility is possible depending on the case at hand. PROGRAM INTFACE collects some of the data generated by PROGRAM BOOSTER and PROGRAM PAYLOAD and produces quantities that involve both booster and payload data. Again, these quantities are needed in PROGRAM SYSRESP and PROGRAM LOADS. PROGRAM INTFACE reflects the coupling between booster and payload through the interface. For example, it calculates the interface modes $[\Phi_I^B]$. PROGRAM FORCE essentially converts the force data into the right format to be used in the integration program PROGRAM SYSRESP. PROGRAM FORCE also contains a number of "flags" which allows for more flexibility. Finally, as mentioned above, PROGRAM LOADS generates member loads and draws on PROGRAM PAYLOAD for load transformation INPUT and on PROGRAM SYSRESP for payload response INPUT.

Each of the six PROGRAMS are independent components of the software package. PROGRAM BOOSTER can be used by an independent booster organization. Similarly, PROGRAM PAYLOAD can be used by an independent payload organization. PROGRAM INTFACE, PROGRAM FORCE and PROGRAM SYSRESP can be used by an independent integration organization while PROGRAM LOADS can be used by any organization that is responsible for loads calculations. Because each of the PROGRAMS is compatible with the other PROGRAMS it is also possible for one organization to use the entire package in sequence.

Several versions of the software package are available. All of these versions make use of the FORMA library. Two versions are available on the CDC computer (Dense-and Partition-Logic). One version is available on the VAX computer (Dense) and one version is available on the UNIVAC system (Partition-Logic).

This section was intended to give the reader a general idea of how the software package is structured. It is not intended to be a detailed user guide. The Final Report of this contract will contain a detailed user guide as well as the actual listings of all the PROGRAMS and associated SUBROUTINES. At this point, the software package is still in a "check-out" phase and is still undergoing minor changes.

As we shall see in subsequent sections, the software package has already been used on several examples and the general structure as described in this section is final.

3. NUMERICAL EXAMPLES

This section we shall discuss a simple sample problem which is used for the initial check-out of the software package. Furthermore, we shall briefly present the results of a realistic defense payload integration analysis which was conducted using the direct integration technique. Both of these sample problems are relatively small in terms of the number of modal coordinates. However, results produced by standard techniques are available and allow us to make a comparison of both techniques. The Final Report will contain a large scale analysis of the Shuttle Orbiter carrying two payloads namely: the Space Telescope and the OMS Kit.

The first example is depicted in Figure 3. The booster B consists of 18 pipe segments. The mass of each segment is equally divided between the end points of the segment. If we only keep translational dofs then the free booster has 57 dofs and the "cantilevered" booster has NB = 54 dofs. Similarly, the payload P consists of 7 pipe segments and NP = 21. Because there are 3 rigid body modes, we have a determinate interface and IF = 3. The parameters for a booster pipe segment are:

$$E=6.89\times10^{6}kN/m^{2}, \rho=2.77\times10^{2}kg/m^{3}, A_{body}=1.93\times10^{-2}m^{2},$$
$$A_{wing}=4.17\times10^{-3}m^{2}, L=0.762m \quad J_{o}=8.325\times10^{-4}m^{4}$$

Similarly, for a payload pipe segment:

$$E=6.89\times10^{6}kN/m^{2}, \rho=2.77\times10^{2}kg/m^{3}, \ A=4.05\times10^{-3}m^{2}$$

$$L=0.762m, \ J_{o}=1.249\times10^{-6}m^{4}$$

Using the above data, a finite element model was derived for both the cantilevered booster and the cantilevered payload. Solving the eigenvalue problem yields booster frequencies ranging form 1 Hz to 106 Hz and payload frequencies from 1 Hz to 104 Hz. In this particular example we used zero initial conditions and applied loads to stations 16 and 17 in the x, y, and z-directions (444822xcos(i50t)N, i=1,6).

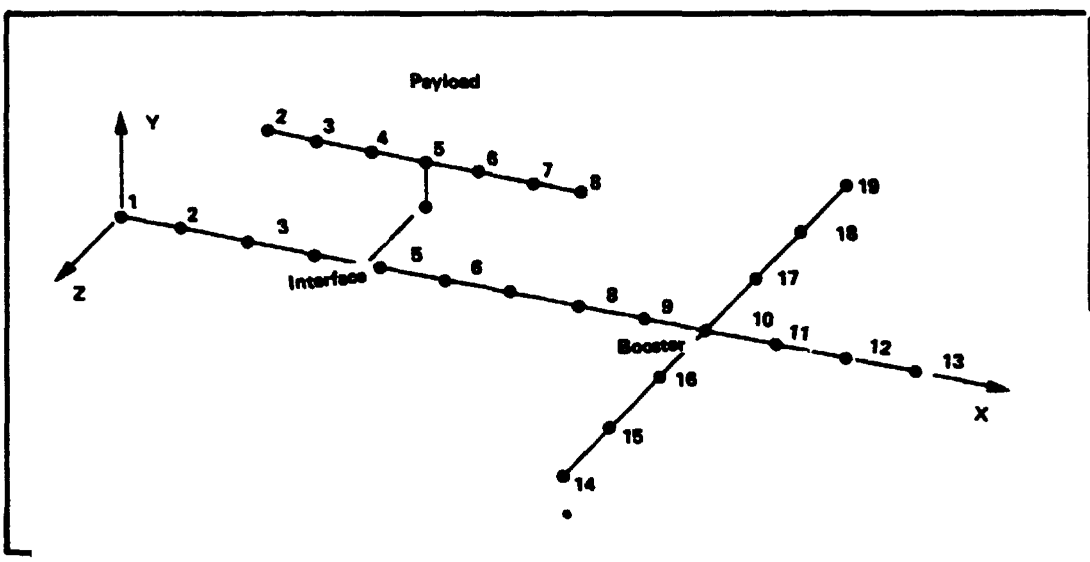

Figure 2 Sample Problem: Booster and Payload

The accuracy of the adapted Newmark-Chan-Beta routine was checked by comparing the response results from PROGRAM SYSRESP with those obtained from a fourth order Runge-Kutta (Gill modification) routine using the same step size. The results compare very well. Table I shows some of the results for a step size h = 0.001 seconds. It should be pointed out that a phase shift in the response was observed . This is to be expected and is inherent to the numerical technique used. However, this phase shift does not affect the value of the maximum or minimum loads in an element. It may slightly affect the time at which this maximum or minimum occurs, but this is of little consequence. Indeed, it is fair to say that in practice every numerical integration technique produces a phase shift when a time step is used consistent with a cut-off frequency.

Next, we compared computer cost of the present method with that of the conventional approach. The conventional "full-scale" approach first calculates the so-called "modal modes and frequencies" (i.e. the system modes from Equation (10)). Then, a numerical scheme (e.g. Runge-Kutta) is used to determine the response from the uncoupled system equations. For the present example, the cost of the direct integration routine to determine the response is less by a factor of 10 compared to the conventional approach. In the Final Report we hope to include a study of how this factor relates to the size of the system and the number of time points and interface dofs.

We also compared the cost of the load calculations. The improved technique decreases the cost by a factor of 12. Again, at this point, it is hard to tell how this factor will change when the booster/ payload system represents a more realistic configuration. Also, it may be hard to compare cost factors for large systems from a logistic point of view. Indeed, payload organizations currently deliver load transformations which are not consistent with the present improved approach. Therefore, it is often impossible to generate the appropriate quantities required for use in the present approach, for lack of certain information. It should be noted that this is only a logistics problem and changes could easily be accommodated.

Table II lists some of the load results obtained for this example.

Again, note that a phase shift is present (although not noticible at the interface). The maximum loads however, compare extremely well (i.e. a relative error of less than 0.1%).

In conclusion, we can state that the entire direct integration routine (i.e. response plus load calculations) is less expensive by roughly a factor of 10 compared to the conventional technique. Note that the analysis was performed on both the CYBER and VAX computer systems. The analysis of a Defense booster/payload system was also completed. The model consisted of a 261 degree of freedom payload model and a 92 degree of freedom booster model. A cut-off frequency of 50 Hz was chosen, resulting in a coupled booster/payload model containing 27 cantilevered booster modes and 55 cantilevered payload modes. There are 6 interface degrees of freedom, which makes the interface determinate. The entire analysis was performed on the VAX computer system.

The results were very encouraging. The accuracy of the maximum loads was excellent (i.e. the relative error compared to the standard technique was < 0.5%). The cost again, was approximatley less by a factor of 10.

In conclusion, we can state that the new approach shows encouraging results which warrant its application to larger booster/payload systems. Indeed, plans were made to apply the present technique to a number of Defense Systems and also to a STS-System. We intend to report on the results in the Final Report of this contract.

4. FINAL REMARKS

In this final section we wish to collect a few relatively unrelated observations.

First of all, there is the question of system modes and frequencies. Indeed, sometimes the payload integration effort is part of a larger program involving the solution of problems for which knowledge of the booster/payload system modes is required. As stated before, the present payload integration method does not require the calculation of the system modes. However, these modes and frequencies can always be calculated from Equation (10). Usually, a one time calculation should be sufficient and no need exists to recalculate these system modes for every load cycle. Furthermore, the system response is already known and could help to reduce the cost of solving the system eigenvalue problem in many cases where a significant percentage of booster modes do not couple with payload modes and vice-versa.

Next, we would like to address a problem related to the practical application of payload integration methods, in particular in the case of the Space Transportation System. As shown in Section 4 of Chapter I, the payload integrator must receive from the booster organization a set of cantilevered booster modes. In theory, this does not present any problem. In practice, however, the payload integrator often has to consider several alternative sets of interface points for possible connection of the payload. For every different interface there is a corresponding different set of booster modes. For reasons of logistics and cost it is virtually impossible to generate a different set of modes every time the interface changes. Therefore only one set of cantilevered booster modes is generated containing all possible interface points. As an example, let us consider a payload that has 7 interface dofs. but could be attached to the booster at 36 different dofs. That means the payload integrator has to select 7 appropriate dofs. out of the 36. The booster organization then could generate a set of cantilevered booster modes about the 36 interface dofs. As can be easily seen this creates a problem when it comes to implementing the theory of Section 4 in Chapter I.

This could be construed as a disadvantage of using cantilevered modes for the booster. Indeed, if one would use free booster modes in an integration technique then this problem of changing booster modes does not exist. However, as we shall show in the Final Report, this particular problem can easily be remedied. Similarly, the problem of multiple payloads can also be addressed in a satisfactory manner. Clearly, the case of superfluous interface dofs. on the booster side and the case of multiple payloads requires a substantial change in the analytical write-up as well as in the computer program code. We shall report on these changes in the Final Report.

The next subject deals with the cost of the response routine i.e. PROGRAM SYSRESP. From Section 4 of Chapter I it follows that the execution time of PROGRAM SYSRESP is proportional to IF, NB, NP and the number of time steps necessary to integrate over the desired time interval. The Final Report will contain a more detailed operation count and an approximate formula for the estimated execution time. At this point it should be noted that IF, NB, and NP are important factors in determining the cost of the integration routine. Indeed, it is not difficult to see that if IF is small compared to NB and NP the execution time goes down considerably. Similarly, the smaller NB and NP the less the cost. This is one clue to a possible short-cut method. Indeed, in many cases the coupling between the booster and the payload is limited. Numerically, this means that some rows of B and/or P will have elements equal to zero or close to zero, so that that particular row is decoupled from the system thereby effectively reducing the size of B and P without all the zero and "near zero" elements. This approach was also reported on in the Monthly Progress Report, Issue 22, Reference [12]. The question then is to develop a criterion defining what a "near zero" element is. There are many other ideas for developing short-cut methods some of which are outlined in Reference [3].

It is our intention to include a chapter on short-cut methods in the Final Report.

TABLE I
COMPARISON OF FOURTH-ORDER
RUNGE-KUTTA TECHNIQUE AND
NEWMARK-CHAN-BETA TECHNIQUE

DOF	Time (sec)		Runge-Kutta	Newmark-Chan-Beta	Relative Error (%)
21	0.01	Acc. (cm/sec^2)	156.5	155.8	0.46
		Vel. (cm/sec)	-0.5626	-0.5686	1.06
		Dis. (cm)	-6.126^{-3}	$-6.094\ 10^{-3}$	0.52
3	0.01	Acc.	$-6.112\ 10^{4}$	-6.112^{4}	$4.16\ 10^{-6}$
		Vel.	$-2/746\ 10^{2}$	$-2.746\ 10^{2}$	$9.25\ 10^{-6}$
		Dis.	-0.787	-0.792	0.65

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TABLE II
COMPARISON OF CLASSICAL AND IMPROVED LOADS CALCULATION TECHNIQUES

Element	Time (sec)	DOF	Loads (N) Classical Method	Loads (N) Improved Method	Relative Error (%)
Interface 1-5	0.01	1	0.646	0.646	0
		2	-0.646	-0.646	0
		3	0	0	0
		4	0	0	0
		5	$-3.929\ 10^{-2}$	$-3.929\ 10^{-2}$	0
		6	$3.929\ 10^{-2}$	$3.929\ 10^{-2}$	0
		7	-0.589	-0.589	0
		8	-0.589	-0.589	0
		9	1.060	1.060	0
		10	-1.060	-1.060	0
		11	-15.90	-15.90	0
		12	-15.90	-15.90	0

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